AD-784 814

ATMOSPHERIC MOISTURE PARAMETERIZATION

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Center (Air Force)
Washington, D. C.

January 1974

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Special acknowledgment and appreciation is extended to Dr. H. R. Eyers, Professor of Meteorology, Texas A & M University and to the University of Chicago Press, Chicago, Illinois who graciously allowed several illustrations from "Elements of Cloud Physics" to be used in this study.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER USAFETAC TN 74-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD 784814
4. TITLE (and Subtitle) Atmospheric Moisture Parameterization		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert D. Smith, Captain, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS USAF Environmental Technical Applications Center, Bldg 159, Navy Yard Annex Washington, DC 20333		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Headquarters Air Weather Service (MAC) Scott Air Force Base, Illinois 62225		12. REPORT DATE January 1974
		13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Requirements exist for estimation of the spatial distribution of liquid and solid water in the atmosphere. Evaluation of previous research indicates that the magnitude of the water at a point can be approximated from the temperature and the type of cloud that exist at that point along with the relative position of the point in the cloud itself. Thermodynamic phase of the water, what portion is liquid or solid, can be generalized from the temperature of the point. The drop-size distribution can be determined by assuming that the available water is found in distributions typical of various types of clouds.

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ATMOSPHERIC MOISTURE PARAMETERIZATION

SECTION A — LIQUID WATER CONTENT

1. Introduction.

A number of studies processed recently have required to some degree the specification of the configuration of moisture in the atmosphere. This configuration has an impact in many areas of which electromatnetic attenuation, clear line of sight, dynamic loading, and icing are just a few. Based on this motivation several investigations have been made into the manner in which moisture is portrayed in meteorological considerations.

Condensed moisture in the atmosphere is described by two parameters, liquid water content (LWC) and drop-size distribution. Liquid water content refers to the magnitude of liquid water in a particular volume of air,whereas drop-size distribution indicates the spatial distribution by drop size of the LWC of that volume. At this point it should be stressed that any reference to LWC in this report includes both liquid and solid forms of moisture. Measurements of LWC of the solid form refer to the equivalent liquid content, unless otherwise specified.

A number of pertinent factors are involved in the distribution of liquid water within the atmosphere; therefore, a discussion of these specific factors is essential if one is to arrive at a method for determining this distribution.

2. Magnitude of Liquid Water Content.

The important factors controlling the magnitude of the liquid water content are as follows:

a. Weight. In the vapor state, water behaves as a constituent of the air; however, when the water vapor condenses into its liquid or solid form, it precipitates out readily because of the large (25,000 times) increase in density compared to other air molecules. The rate of precipitation of liquid or solid water is dependent upon the magnitude of the liquid water content.

b. Condensation. The amount of water that can condense out of a parcel of air depends upon the amount of water vapor in the parcel and the reduction of pressure and temperature undergone by the parcel. The amount of water obtainable from a parcel by this process is termed the adiabatic LWC. Although this process can be used to determine the amount of water available in a parcel of air, it cannot be used to determine the distribution of LWC in a parcel because of the movement of the water after condensation. Ackerman [1] and Warner and Squires [21] have discussed this process thoroughly in reviewing the factors involved in LWC determination.

c. Vertical Motion. The effects of vertical motion on liquid-water distribution must be considered from two viewpoints. The first concern is the fall velocity of the droplets and the second is the vertical motion of the air.

The fall velocity of the droplets depends on the effect of gravity and the density of the air. The Smithsonian Meteorological Tables [15] show that the terminal velocity varies from 27 centimeters per second for a droplet with a radius of 50 micrometers to 9 meters per second for a droplet with a radius of 2500 micrometers. This fall velocity is a function of the radius of the droplet and the aerodynamic drag. These velocities are graphically shown in Figure 1, after Byers [3].

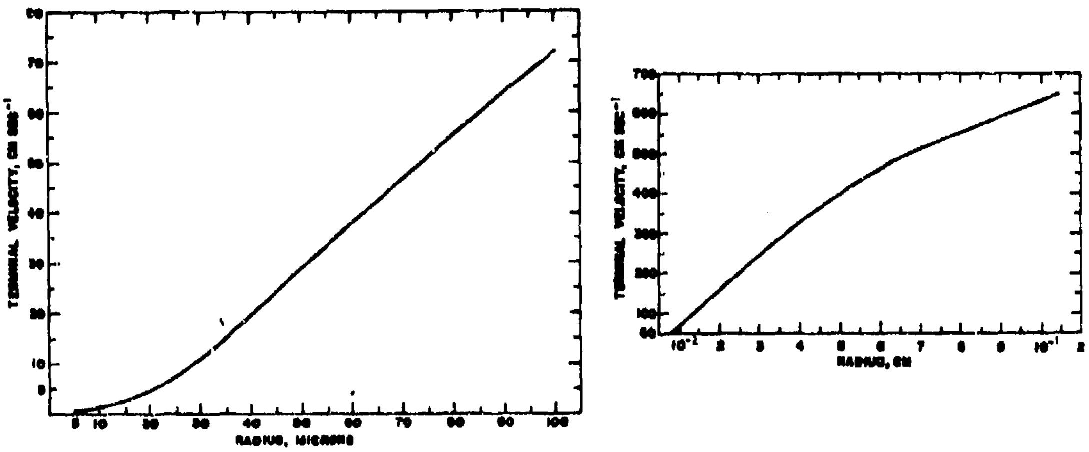


Figure 1. Terminal Velocity of Spheres of Unit Density as a Function of Their Radii in Two Different Size Ranges [3].

Droplets with radii less than 50 micrometers obey Stokes' Law because the viscous forces are more significant than aerodynamic drag at these small radii. On the other hand, very large droplets are subject to aerodynamic instability which causes them to break up into smaller droplets.

The effect of fall velocity of the drops and vertical air motion is shown in Figure 2 (from Kessler and Baumgarner [11]) by indicating the amount of LWC that can accumulate in a cloud created by a known mean vertical motion. The K_5 values in the figure are related to the entrainment

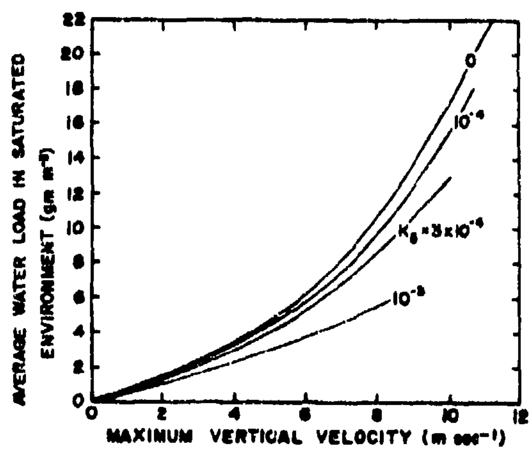


Figure 2. Average Liquid Water Content in a Vertical Column 10 Km High, in Relation to the Maximum Vertical Air Speed and Mixing Rate K_5. The diagram applies to steady state conditions in saturated model updraft columns in saturated environments [11].

Table 1. Frequency of Liquid Water Content in Clouds as Function of Temperature (%)

Water Content g/cm^3	Interval of Temperature (in degrees)								
	-25.0 to -20.1	-20.0 to -15.1	-15.0 to -10.1	-10.0 to -05.1	-5.0 to -0.1	0.0 to +4.9	5.0 to +9.9	10.0 to +14.9	15.0 to +19.9
< 0.05	16.7	22.5	14.5	9.2	6.0	4.9	3.8	6.3	
0.05 - 0.10	47.7	33.75	28.6	26.1	21.4	17.0	16.2	13.9	
0.11 - 0.15	33.3	17.5	23.1	17.9	18.0	14.4	11.5	11.4	90%
0.16 - 0.20		11.25	13.6	13.9	13.9	10.5	11.9	17.7	75.0
0.21 - 0.25	8.3	7.5	4.8	10.3	10.6	10.2	9.8	7.6	
0.26 - 0.30		3.75	5.3	6.1	8.2	8.8	9.1	7.6	75%
0.31 - 0.35		1.25	4.0	5.8	5.2	6.8	5.1	6.3	
0.36 - 0.40			2.0	3.4	4.1	4.7	6.4	7.6	
0.41 - 0.45		1.25	1.5	2.9	3.0	3.3	4.3	6.3	
0.46 - 0.50		1.25	0.9	1.5	1.9	3.0	2.1	6.3	
0.51 - 0.55			0.4	1.2	1.9	3.0	3.0	1.3	
0.56 - 0.60			0.9	0.2	1.5	2.1	2.1	2.5	
0.61 - 0.65			0.2	0.6	1.0	1.4	3.0		
0.66 - 0.70			0.2	0.2	0.8	1.2	2.1		
0.71 - 0.75				0.4	0.8	2.1	1.3		
0.76 - 0.80				0.1	1.0	1.2	1.7	1.3	
0.81 - 0.85						1.4	1.3		
0.86 - 0.90				0.1		0.2	1.7	1.3	
0.91 - 0.95					0.1	0.2			
0.96 - 1.00				0.1	0.3	0.5	0.8	1.3	
1.01 - 1.05					0.1	0.8	0.8		
1.06 - 1.10						0.2			
1.11 - 1.15						0.9	0.4		
1.16 - 1.20					0.1	0.2		0.3	
1.26 - 1.30							0.4		
1.51 - 1.55					0.1	0.2			
1.56 - 1.60							0.4		
> 1.60						0.8	1.3		
No. of Cases	12	80	455	855	785	429	234	79	4

of unsaturated air into the cloud.

Although vertical motion can be used to obtain a reasonable approximation of LWC, vertical motion is one of the more difficult measurements to obtain because of dynamic considerations.

d. Temperature. Since the amount of water vapor in a parcel is related to the temperature of the parcel, temperature measurements can provide an indication of the magnitude of LWC in a parcel. Tables 1, 2, and 3 (Khrgian [12]) show the percentage occurrences of amounts of liquid water found at various temperature intervals within clouds. Tables 2 and 3 refer to specific cloud types.

Unfortunately, the use of temperature measurements alone is not enough to obtain the magnitude and distribution of LWC, because it cannot take into account the other processes involved in the formation of liquid water. For example,

Table 2. Frequency of Liquid Water Content in Sc, St, and Ac Clouds as Function of Temperature (%)

Water Content g/cm^3	Interval of Temperature (in degrees) -25.0 to -20.1	-20.0 to -15.1	-15.0 to -10.1	-10.0 to -05.1	-05.0 to -0.1	0.0 to +4.9	5.0 to +9.9	10.0 to +14.9	15.0 to +19.9	
< 0.05	29.3	23.6	16.1	10.6	6.0	4.8	4.2	5.7		
0.05 - 0.10	29.3	35.0	30.3	28.9	23.2	17.4	15.7	12.2		
0.11 - 0.15	25.9	13.2	2.4	11.4	16.7	13.4	11.8	9.4	20.0	
0.16 - 0.20	3.4	9.8	12.6	14.6	14.5	11.9	10.6	18.9	20.0	
0.21 - 0.25	3.4	7.5	5.3	10.6	10.4	9.7	11.8	14.1	13.33	50%
0.26 - 0.30	5.3	5.7	5.9	7.2	7.3	8.2	9.2	8.5	13.33	
0.31 - 0.35	1.7	3.4	3.3	6.0	6.0	7.2	6.5	6.6		
0.36 - 0.40	1.7	0.6	1.8	3.8	3.7	4.8	7.2	6.6		
0.41 - 0.45		0.6	1.4	2.8	3.0	3.7	4.2	5.7	13.33	75%
0.46 - 0.50		0.6	0.7	1.7	1.9	3.8	2.0	5.8	20.0	
0.51 - 0.55			0.3	1.2	1.9	2.5	2.9	0.9		
0.56 - 0.60			0.7	0.2	1.7	2.3	1.6	1.9		
0.61 - 0.65			0.1	0.6	1.0	1.2	2.6			
0.66 - 0.70			0.1	0.5	0.5	0.9	2.0			
0.71 - 0.75				0.2	0.6	2.3	1.0			
0.76 - 0.80				0.09	0.9	1.1	1.3	0.9		
0.81 - 0.85				0.09	0.07	1.5	1.0			
0.86 - 0.90					0.13	0.15	1.3	0.9		
0.91 - 0.95			0.1		0.19	0.3				
0.96 - 1.00			0.1	0.09	0.2	0.3	0.6			
1.01 - 1.05					0.07	0.6	0.6	0.9		
1.06 - 1.10						0.3				
1.11 - 1.15						0.6	0.33			
1.16 - 1.20					0.07	0.3		0.9		
1.26 - 1.30							0.33			
1.51 - 1.55					0.07	0.15				
1.56 - 1.60							0.33			
> 1.60						0.5	1.0			
No. of Cases	58	174	701	1240	1484	649	306	106	15	

the displacement of the parcel in time is not considered; therefore, the degree of supersaturation and resulting condensation cannot be inferred. Likewise, the velocity of the liquid water from the point of condensation is not considered. Even with its limitations, however, temperature measurements can be very useful for some work.

3. Evaluation of Available Data.

An extensive review of prior work in the area of liquid water content produced a great amount of information but no concrete method for LWC specification. The majority of the work done in LWC measurements are isolated studies of particular types of clouds or measurements with a specific objective.

Warner [22] and Warner and Squires [21] advocate the specification of the LWC of cumuliform clouds as a percent of the adiabatic LWC varying with height.

Table 3. Frequency of Liquid Water Content in Ns and As Clouds as Function of Temperature (%)

Water Content g/cm^3	Interval of Temperature (in degrees)								
	-25.0 to -20.1	-20.0 to -15.1	-15.0 to -10.1	-10.0 to -05.1	-05.0 to -0.1	0.0 to +4.9	5.0 to +9.9	10.0 to +14.9	15.0 to +19.9
< 0.05	0.7	11.5	5.2	8.8	3.5	0.3	2.3	9.5	
0.05 - 0.10	26.1	24.6	31.0	20.3	23.3	12.2	12.7	9.5	
0.11 - 0.15	26.1	24.6	18.4	20.3	15.1	13.8	5.7	4.8	
0.16 - 0.20	13.1	9.9	17.2	16.3	13.1	11.3	12.7	14.3	
0.21 - 0.25	4.3	11.5	12.1	13.4	11.0	11.3	10.3	9.5	
0.26 - 0.30	17.4	8.2	2.9	6.2	10.4	8.4	16.2	19.0	90%
0.31 - 0.35	4.3	1.6	6.3	5.9	8.3	10.9	5.7	14.3	
0.36 - 0.40		4.9	1.1	2.9	4.3	6.1	3.4		
0.41 - 0.45		1.6	2.9	3.4	2.5	6.1	6.9	4.8	75%
0.46 - 0.50		1.6	1.1	0.3	1.3	5.1	8.0	4.8	
0.51 - 0.55			0.6	1.3	2.3	3.2	2.3		
0.56 - 0.60			0.6	0.6	1.2	3.9	2.3		
0.61 - 0.65					0.8	1.3	1.15	4.8	
0.66 - 0.70			0.6		0.3	1.6	4.6		
0.71 - 0.75				0.3	0.8	2.3	1.15		
0.76 - 0.80					0.5	1.0	1.15		
0.81 - 0.85					0.5	0.3	1.15		
0.86 - 0.90						0.3			
0.91 - 0.95					0.2				
0.96 - 1.00						0.3			
1.01 - 1.05					0.2				
1.06 - 1.10					0.2	0.3		4.7	
1.11 - 1.15					0.2		1.15		
1.16 - 1.20									
1.26 - 1.30							1.15		
1.51 - 1.55									
1.56 - 1.60									
> 1.60									
No. of Cases	23	61	174	306	604	311	87	21	

This process produces results which fit reasonably well the profiles observed in four different cumulus clouds as shown in Figure 3, after Warner [22]. The variation of LWC with height is well defined by this process.

A number of researchers, notably Chang and Willand [6], Khrgian [12], and Mason [17], have developed tables which specify average values for various cloud types. The table from Chang and Willand [6] is reproduced as Table 4. These tables are sufficient for differentiating LWC from one cloud type to another but not for specifying the magnitude of LWC for clouds under varying atmospheric conditions.

In an effort to establish some general criteria for estimating LWC from various atmospheric parameters, the data from a number of reports were combined and evaluated. Information from papers by Warner [20], Ryan [18], MacReady and

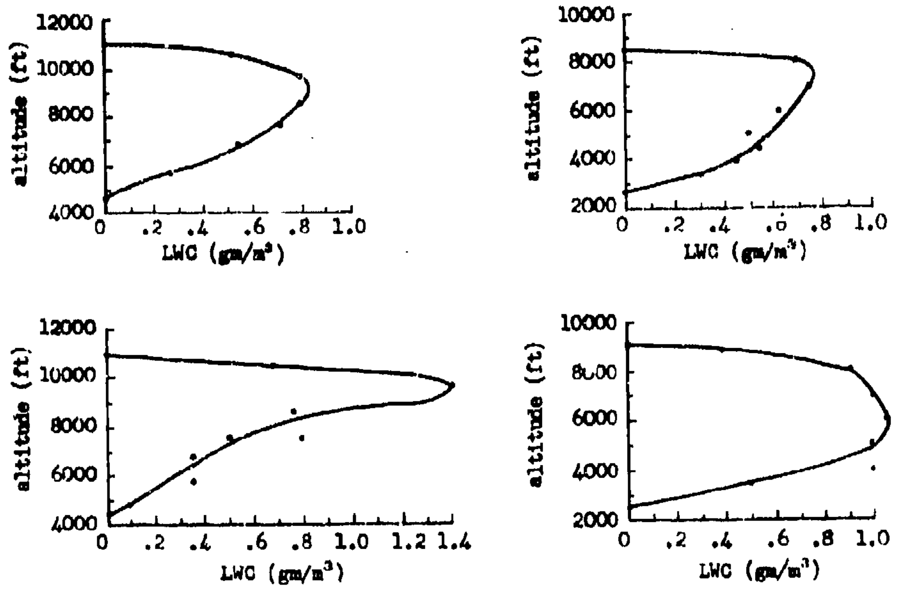


Figure 3a. Variation of Peak Water Content with Height. [22]

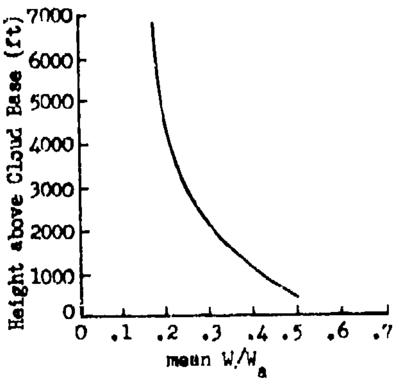


Figure 3b. Mean Ratio W/W_a versus Height above Base. [22]

Takeuchi [16], Knollenberg [13], Squires [19], Mason [17], Weickmann and aufm Kampe [24], Kunkel [14], and Cannon and Sartor [5] was collectively processed to look at various relationships. Comparison of variations of LWC with height, with height above cloud base, with average droplet size, and with temperature were made for specific cloud types. Other than the general variations of LWC with height in cumulus clouds, no significant generalizations could be drawn from this material. The variation of the equipment, measurement techniques, and processing of the data between the various researchers is most likely the reason for the resulting inconsistencies found in the combined data.

Table 4. Models of Cloud Parameters [6].

Cloud Type	Base (m)	Top (m)	Modal Radius (cm, (μ)	Density or Liquid Water Content (g/m³)
Cumulus	500	1,000	10.0	0.50
	1,000	1,500	10.0	1.00
	1,500	2,000	10.0	0.50
Stratocumulus	500	1,000	10.0	0.25
Stratus	150	1,000	10.0	0.25
Cumulonimbus	0	300	400.0	6.30
	300	1,000	20.0	7.00
	1,000	4,000	10.0	8.00
	4,000	6,000	10.0	4.00
	6,000	8,000	10.0	3.00
	8,000	10,000	40.0	0.20
Altostratus	2,400	2,900	10.0	0.15
Altocumulus	2,400	2,900	10.0	0.15
Cirrus - Arctic	5,500	6,000	40.0	0.10
- Mid-Lat.	6,500	7,000	40.0	0.10
- Tropical	7,500	8,000	40.0	0.10
Cirrostratus - Arctic	4,000	6,000	40.0	0.10
- Mid-Lat.	5,900	7,000	40.0	0.10
- Tropical	6,000	8,000	40.0	0.10
Nimbostratus	0	500	200.0	1.00
	500	1,000	10.0	2.00
	1,000	2,000	10.0	3.00
	2,000	4,000	10.0	2.00

Since the only statistically significant relationship between LWC and atmospheric parameters were the relationship relative to temperature as reported by Khrgian [12], this factor, in association with the variation of LWC with cloud type and with height above the cloud base, was used by Feddes [8] to infer LWC at a point in the atmosphere. Table 5 and Figure 4 represent the techniques developed for Feddes' study. The maximum LWC is defined by the cloud type and temperature using the values from Table 5. The LWC for the point under consideration is found by determining the percentage of LWC based on the height above the cloud base (and whether it is currently precipitating) from curves similar to Figure 4 for each cloud type. Note that in the case of precipitation, the cloud LWC will be that portion to the left of the nonprecipitating curve where precipitation will be the remainder of the total LWC.

Subsequent to Feddes' study, the data developed by Blau, et al [2] from the numerous flights by the NASA Convair 990 aircraft were obtained and evaluated. These data differ from those in the previously described evaluation in that the

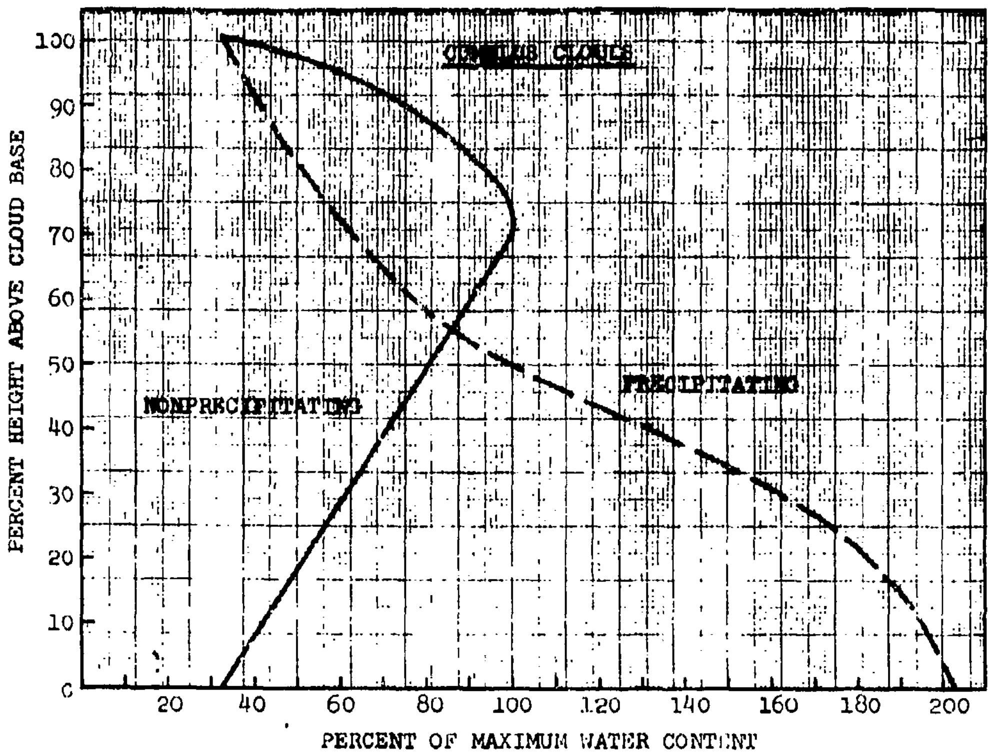


Figure 4. Profile of Percent of LWC with Height Above Cloud Base for Cloud Indicated.

Table 5. Maximum Liquid Water Content (LWC) that can be Expected in Cloud Types Given in the Temperature Range Indicated.

CLOUD TYPE	TEMPERATURE RANGE <-25	-25 to -20	-20 to -15	-15 to -10	-10 to -5	-5 to 0	0 to 5	5 to 10	10 to 15	>15
ST	.10	.15	.20	.25	.30	.35	.40	.45	.50	.50
SC	.20	.30	.40	.45	.50	.55	.60	.70	.70	.70
CU	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
NS	.35	.40	.45	.50	.60	.60	.75	.90	.90	.90
AC	.25	.30	.35	.40	.40	.45	.60	.70	.70	.70
AS	.15	.20	.25	.30	.30	.35	.40	.50	.50	.50
CS	.15	.15	.15	.20	.20	.20	.25	.25	.25	.25
CI	.10	.10	.10	.10	.15	.15	.15	.20	.20	.20
CC	.05	.05	.05	.05	.10	.10	.10	.15	.15	.15
CB	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50

NASA information consisted of measurements made by the same instrument using the same techniques in various types of clouds. Liquid water content measurements made by these researchers verified the information of the average values for various cloud types previously discussed and given in Tables 1, 2, and 3. Sufficient measurements did not exist for clouds other than cumulus to give variations with temperature and height.

SECTION B — THERMODYNAMICS OF PHASE CHANGES

1. Prior Research.

Many cloud physicists have contributed to the study of the thermodynamics of phase changes of water in clouds. Byers [3] and Khrgian [12] have covered the subject well and Byers deals extensively with the microphysics of ice formation in clouds. He points out the importance of considering phase changes from vapor to solid as well as liquid to solid.

Hess [9] reviews the physics of latent heat release that results from the change of phase from liquid to solid and vapor to solid. He also points out the importance of these heat sources in cloud dynamics.

Byers [3] reviews the principle that for the same temperature, the vapor pressure over ice is less than that over water, and therefore, in a mixed and supersaturated water-ice environment, ice crystals will grow at the expense of water droplets. He also points out that under laboratory conditions, supercooled water has been observed down to temperatures of -40°C. This factor establishes a transition zone where both liquid and solid water are found in the atmosphere. Figure 5, from Khrgian [12], shows the results of observations made in Russia delineating the temperature where various mixtures of ice and water clouds are found. This condition applies to those clouds which are primarily liquid clouds since cirrus clouds are, by definition, composed of ice crystals.

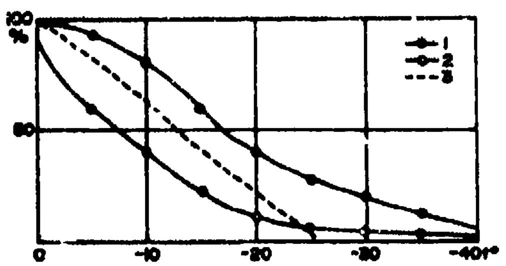


Figure 5. Average Frequencies of Appearance of the Supercooled and Mixed Phases over Russia [12].

1 - liquid and mixed clouds together

2 - liquid clouds (after A. M. Borovikov and L. G. Sakhno)

3 - liquid clouds (after Peppler)

2. Determination Technique.

The technique used to specify thermodynamic phase in clouds is based on temperature and cloud type. Specifically, it is based on Figure 5 where the amount of liquid water is the percent of cloud water defined by the relationship

$$\% \, LWC = -2.5 \, (233-T)$$

where T is expressed in degrees Kelvin.

SECTION C — DROP-SIZE DISTRIBUTION

1. Initial Distribution.

The initial distribution of droplets at condensation will depend strongly on the type and number of condensation nuclei present. If there are no hygroscopic particles available, condensation will depend on spontaneous formation of the embryonic droplets.

a. Homogeneous Nucleation. Homogeneous nucleation occurs when the random motion of water vapor molecules in a highly supersaturated environment results in collisions that produce water droplets. Because the degree of supersaturation required (200% to 800% relative humidity) is so high, its occurrence in the atmosphere is unlikely and, therefore, of little importance in the determination of LWC.

b. Heterogeneous Nucleation. The condensation of vapor onto hygroscopic particles was discussed previously. In this type process the initial distribution of the droplets will be strongly influenced by the distribution of the condensation nuclei. A number of researchers have made measurements of the size and concentration of condensation nuclei. Byers [3], Mason [17], and Khrgian [12] have summarized the occurrence and physical properties of these nuclei as they occur over land and sea. They review the observation that nuclei from marine environments are larger but less numerous than nuclei from continental areas.

From the earlier discussion of the rate of growth of various-sized droplets, the initial distribution of condensation nuclei will largely determine the size distribution of subsequently-formed drops as well as the rate of increase of liquid water content. Evaluation of how the initial distribution changes with time will require discussion of the factors which change the distribution.

2. Change in Drop-Size Distribution.

Three processes have been identified by most researchers as the ones which change drop-size distribution. They are diffusion, coalescence, and collection. Each will be discussed separately.

a. Diffusion. The process of diffusion consists of a net flux of water vapor to previously-formed droplets. This flux is a result of the difference between the vapor pressure of the air and vapor pressure of the droplets. As discussed earlier, the smaller the droplet, the higher its vapor pressure; however, as discussed by Byers [3], this radius-dependent effect becomes insignificant as the droplet radius increases and the vapor pressure of a large droplet approaches that of a plane water surface.

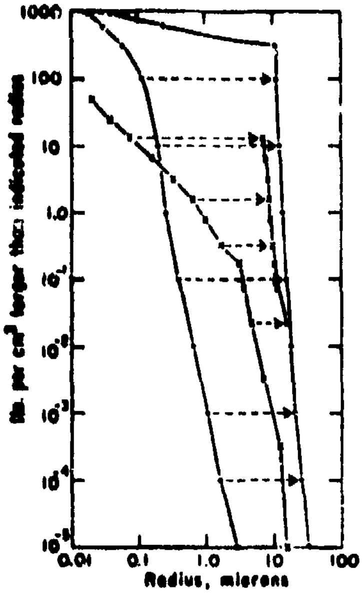


Figure 6. Initial and Final Distributions of Particle and Droplet Sizes as Computed by Mordy (1959) (points marked x) and by Neiburger and Chien (1960) (points with heavy dots). The dashed arrows connect initial with final sizes. (from Byers [3])

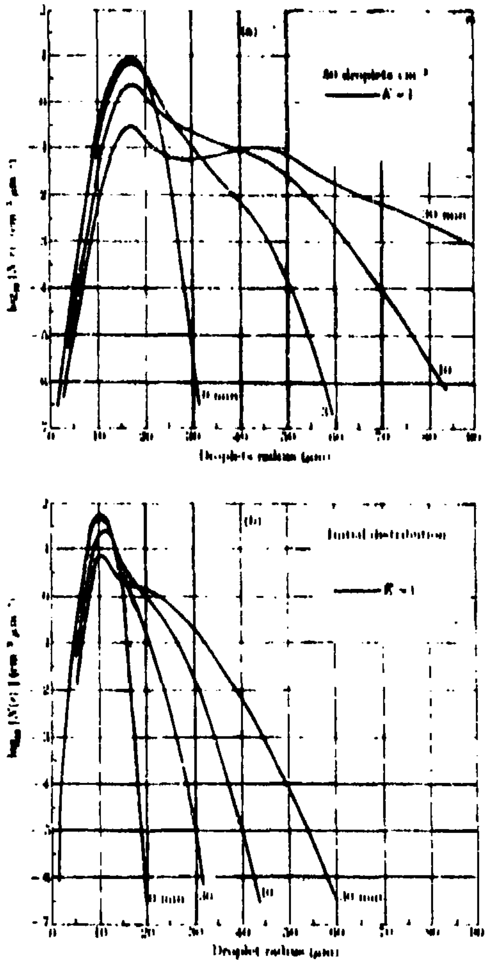


Figure 7. Evolution of Droplet-Size Distribution with Time According to the Theory of Coalescence [23a].

The mass accretion by diffusion, therefore, depends on the available droplet surface; hence, the number and size of the drops. By this process the larger drops will acquire more mass; however, the relative growth of the smaller droplets will be faster than the larger drops. The effects of diffusion will tend to narrow the spectrum of drop-size distribution and move the peak toward the larger radii. This process is shown graphically by Figure 6 taken from Byers [3].

b. Coalescence. Coalescence or coagulation of droplets is the process whereby droplets moving through the air by turbulent motions collide and adhere to form larger droplets. Thus, it is apparent that coagulation depends on the number density of droplets. The higher the concentration, the faster the coagulation proceeds. From this standpoint also, for a particular LWC, the smaller the mean droplet radius, the higher the concentration, therefore, the faster the coagulation rate.

Byers [3] and Mason [17] report that research work has shown that coalescence is more frequent among drops of different sizes than among equal size drops. However, in this report, differentiation must be made between coalescence and collection, which will be discussed in the next paragraph. The effect of coalescence on the distribution of droplets is a broadening of the spectrum by the creation of droplets larger than those found in the initial distribution as well as a shift of the peak of distribution to larger radii. This is typified by Figure 7 shown on the previous page (after Warshaw [23a]).

c. Collection. Collection of droplets is the process where the differential motion of large and small drops cause larger drops to sweep up and accumulate the mass of smaller droplets. This process exists only in the case where there is a variation in droplet motion. This occurs where droplets develop differential vertical motions due to gravity or horizontal motion due to "form" drag.

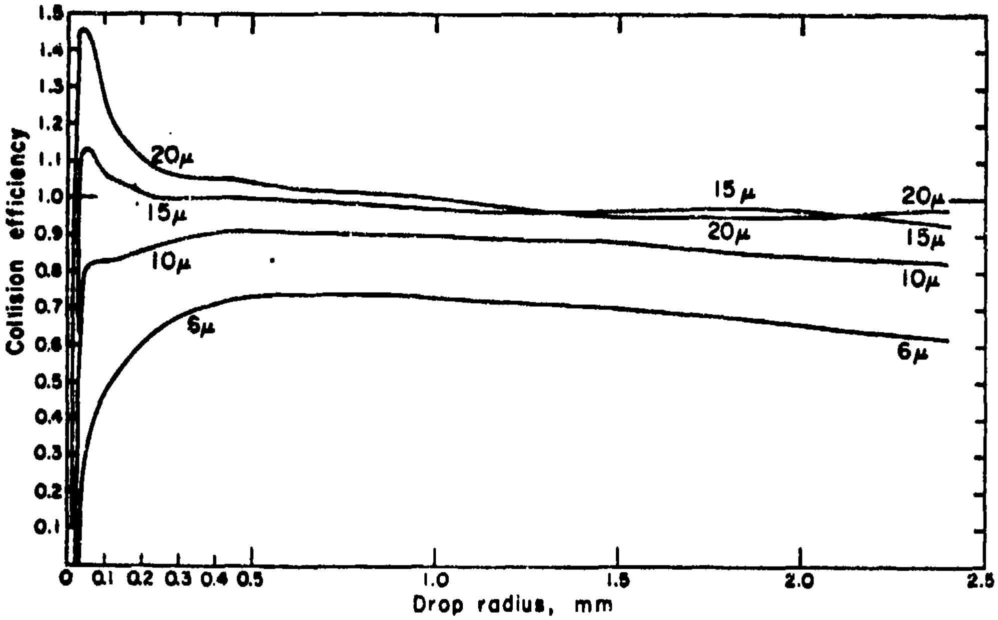


Figure 8. Collision Efficiencies. Collecting-drop radii are indicated on the abscissa. Radii of the collected droplets are indicated by the curves. [3]

Collection is a complicated process, and it has been studied primarily under experimental conditions. Collection efficiency is defined as the fraction of the droplets in the path of a collector drop that collide with the collector. Figure 8 shows the collision efficiencies for various collector and collected drop sizes. Fractions greater than 1.0 occur because of the capture of droplets in the wake of the collectors that have a collision efficiency greater than 0.75.

The collection efficiency is defined as the product of the collision efficiency and the coalescence efficiency. Coalescence efficiency is the fraction of the drops that are captured by the collector drop after collision. In Figure 8, the coalescence efficiency is assumed to be unity, as is the usual case in the atmosphere in the presence of negligible electric fields. Experiments have shown that atmospheric electrical fields, such as occur in thunderstorms, can significantly enhance coalescence efficiencies.

3. Predominant Distribution-Change Mechanisms.

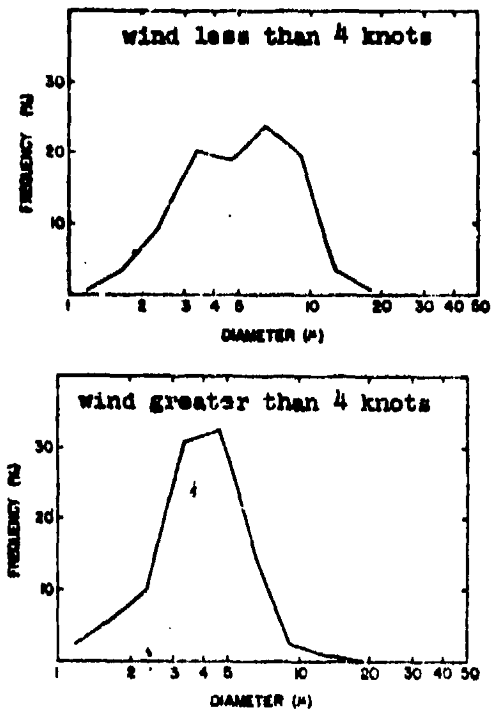
The process which alters the drop-size distribution in the atmosphere is made up of all three of the previously-described changes. All three can logically be expected to be operating at the same time under most conditions; however, each will predominate at certain times and during particular situations.

a. Condensation. During rapid condensation and droplet growth, the predominant mode of distribution change is diffusion. If condensation has only recently begun in an area, most of the droplets will be small, depending, as has been noted, on the size of the available condensation nuclei. During this time droplets have not grown to sufficient size for coalescence to be effective. As the clouds become older, the droplets reach the size where the coalescence process predominates until evaporation begins.

b. Stable Clouds. Stable clouds are those clouds that exhibit a slow rate of change in character. As an example, stratus clouds are considered stable as opposed to the cumulus type that are quite dynamic in change of overall size of the cloud and amount of their LWC. The process of coalescence is predominant in stratiform clouds due to an absence of strong motions, particularly vertical. Figure 9, from Byers [3], gives an excellent example of the difference in droplet distribution in stratus clouds with varying degrees of motion. Clouds with the weaker motion have a broader spectrum which has been developed by diffusion and coalescence and shows the peak of distribution at the larger radii. The peak of the distribution in the cloud with the stronger motion tends to appear near the radius of the drops that are the most efficient collectors.

Figure 10, taken from Byers [3], shows the effects of motion on drop-size distribution. Note that the majority of the droplets in the radiation fog are at the smaller radii, while for the advection fog, the distribution peak is at the larger radii. This shift in the drop-size distribution occurs as a result of enhanced collection with increased air motion.

c. Strong Vertical Motion. The effects of strong vertical motion can best be described by predominance of the collection process. This process, relative to that in stable clouds, is exhibited in Figure 11, from Diem [7]. Note that the clouds with stronger vertical motion have their peaks at larger radii than those with weaker motions; whereas, the more stable clouds have generally broader spectra.



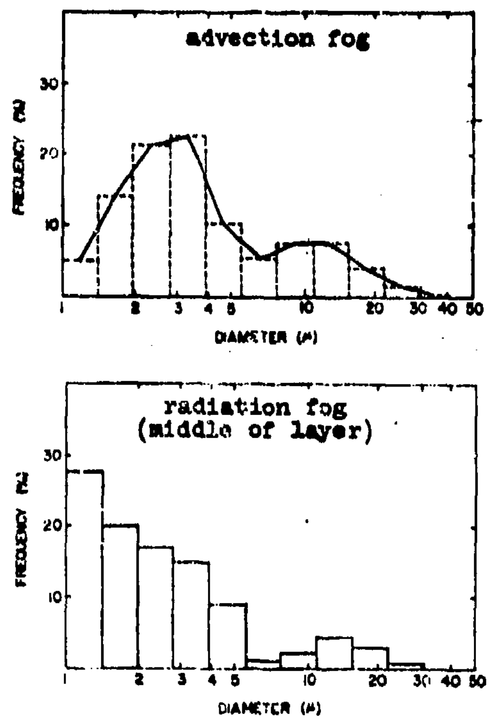
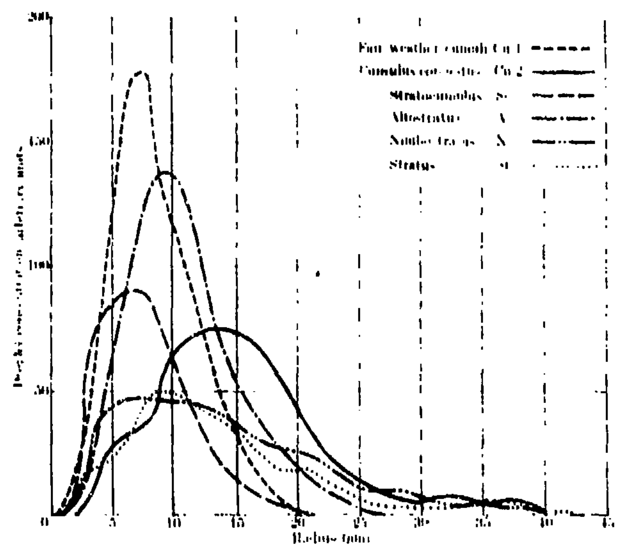


Figure 9. Size Distribution of Droplets in Nonprecipitating Stratus Cloud as Measured by Pedersen and Todsen (1960) at 500 m above Sea Level in Norway. (after Byers [3])

Figure 10. Size Distribution of Droplets in Fog as Measured by Pedersen and Todsen (1960) in Norway. (after Byers [3])

Figure 11. The Mean Droplet-Size Distributions of Various Cloud Types [7].



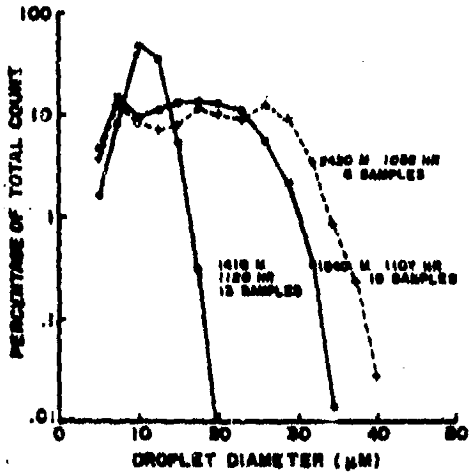


Figure 12. The Average Size Distribution of All Samples Taken at Three Different Levels in a Cumulus Cloud Based at 1200 m and with Tops ~ 2600 m [20].

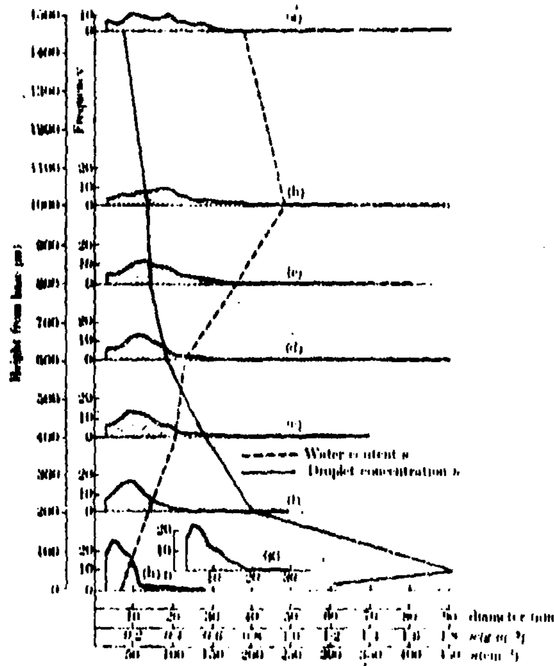


Figure 13. The Droplet-Size Distribution, Liquid Water Content, and Droplet Concentration as Functions of Height in a Cumulus Congestus [25].

As the caption of Figure 11 states, these are representations of mean distributions. This fact can be misleading if the variability of distribution within the cloud is not fully appreciated.

Figure 12 (taken from Warner [20]) shows the variation with height of drop sizes through a cumulus. Note that with increasing height of the cloud, the distribution of drop sizes broadens as the peak droplet size shifts to larger diameters. The shift of peak droplet size occurs because of enhanced coalescence and collection due to the longer path travelled by the majority of droplets at the upper portions of the cloud. The broadening of the drop-size distribution occurs because of increasing entrainment toward the top of the growing cumulus.

Figure 13, from Zaitsev [25], also is a good representation of the variation of distribution and LWC in cumulus congestus. The motion of the air, which generally varies from the motion of the liquid water due to "form drag" and weight of the water, causes this configuration. The distribution of LWC and drop-size distribution in cumulus depends strongly on the pattern and magnitude of the internal wind system of the cloud.

4. Evaluation of Available Data.

Evaluation of the NASA data discussed by Blau et al [2] generally substantiated the mean curves found in Mason [17] and shown in Figure 11. The one significant variation was found in the drop-size distribution of stratus clouds.

Similar flights in maritime stratus at approximately the same temperature and altitude exhibited widely varying drop-size distributions. These variations are shown in Figure 14. It is likely that the variations were due to the different ages of the clouds sampled. Based on the theory of coalescence, the cloud sampled in Flight 1 was the oldest. This again points out that, even in stable stratiform clouds, substantial variations from the mean can be found.

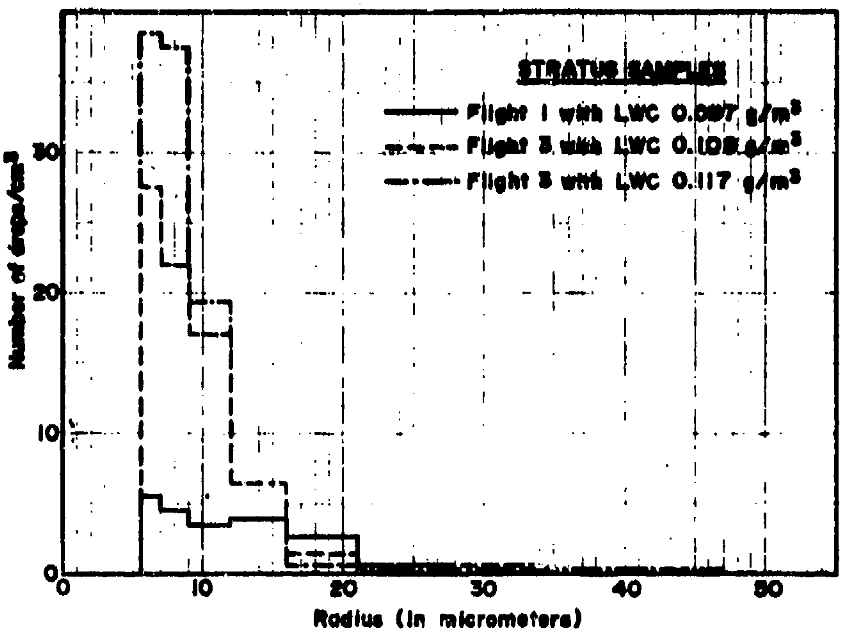


Figure 14. Variations in Drop-Size Distribution of Stratus Cloud.

5. <u>Drop-Size Distribution Determination Technique</u>.

Based primarily on the information obtained from evaluation of drop-size distribution from Blau et al [2], the mean curves of percent of LWC per radius of differing cloud types, as shown in Figure 15 from Diem [7], are the best method for specifying drop-size distribution. The drop-size distribution for varying cloud types proved to be of little value as a tool for determining LWC.

Specifically, the drop-size distribution is determined through the following equation using the value of LWC at each radius

$$\% \text{ LWC} = A\ (r - B)$$

A and B are constants for particular cloud types, while r is the drop radius in micrometers. These constants were derived from the curves in Figure 15, except for cirrus, and are given in Table 6. The values for cirrus were derived from the data from the NASA measurements reported by Blau et al [2].

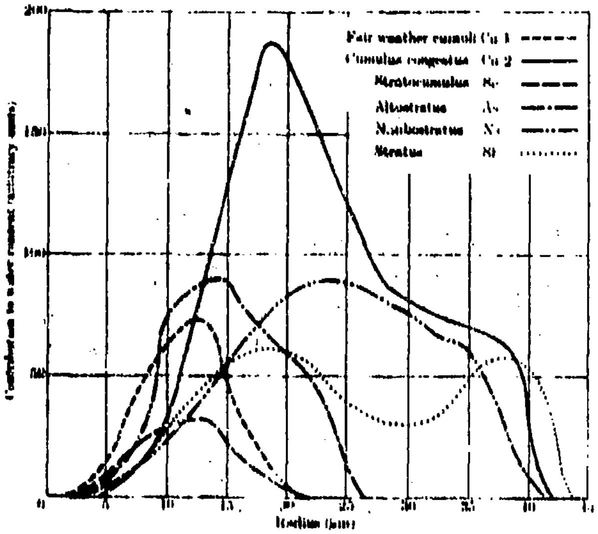


Figure 15. The Contribution Made by Droplets of Various Sizes to the Liquid Water Content of Different Types of Cloud [7].

Table 6. Cloud DSD Parameters.

Cloud Type	A	B
Cumulus	45/ 8	2
Cumulus Congestus	25/ 9	4
Stratocumulus	60/11	2
Altostratus	30/ 7	3
Nimbostratus	54/19	5
Stratus	30/11	6
Cirrus	48/ 5	8

The drop-size distribution for precipitation, as discussed by Kessler [10], can be found from the relationship

$$\dot{N}(r) = 20 \left[\exp \left(\frac{-4.744\ r \times 10^{-2}}{(LWC)^{.250}} \right) \right]$$

where r = drop radius in microns

LWC = liquid water content in g/m^3

$N(r)$ = number of drops per m^3 per micron radius interval

6. Summary.

Atmospheric moisture has a significant impact on all types of equipment and instrumentation that operates in and above the earth's atmosphere. This report has traced the development of theoretical and empirical methods to measure this atmospheric moisture in the liquid and solid state. The relationships developed for moisture parameterization produce a best estimate of liquid and solid water at a point in time and space. These parameterizations will be utilized extensively in modelling the distribution of atmospheric moisture by applying nephanalysis and the more conventional parameters from real time and historic three-dimensional data bases.

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LIST OF SYMBOLS

A	Drop-size distribution parameter
B	Drop-size distribution minimum radius
L_v	Latent heat of vaporization
m_v	Molecular weight of water vapor
$N(r)$	Number density per radius
P	Total pressure
p_i	Partial pressure of i^{th} constituent
p_{vs}	Saturation vapor pressure
q	Specific humidity
R	Universal gas constant
r	Drop radius
T	Temperature
W	Liquid water content
W_a	Adiabatic liquid water content
α	Specific volume
ρ	Density of the air
ρd	Density of dry air
ρw	Density of water vapor

LIST OF USAFETAC TECHNICAL NOTES

Number	Title	Date
73-1	Interim Instructions for the Use of Air Stagnation Weather Charts and Messages (AWS distribution only)	Jan 73
73-2	The Ochaltree Tornado, A Case Study	Mar 73
73-3	Listing of Seminars Available at Hq AWS, AWS Wings, and AFGWC (AWS distribution only) (AD-757543)	Mar 73
73-4	USAFETAC Refractive Index Gradient Summaries (AD-762501)	Apr 73
73-5	Short-Range Weather Forecasting: Recent Developments in Air Weather Service, Suggested Techniques (AWS distribution only)	May 73
73-6	A Resumé on the State of the Art for Snow Forecasting (AD-767214)	Jul 73
74-1	Atmospheric Moisture Parameterization (AD-)	Jan 74